GEI Consultants

Geotechnical
Environmental
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FINAL
Updated Freshwater Aquatic Life Criteria for Selenium

Submitted to:
Virginia Mining Issues Group
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1.0 Introduction

At the request of the Virginia Mining Issues Group, GEI Consultants, Inc. (GEI) has prepared this analysis in support of potential updates to state-wide water quality standards for selenium (Se).

Selenium is an essential micronutrient required by most aquatic and terrestrial species in order to maintain metabolic function (U.S. Environmental Protection Agency [EPA] 2004). It occurs in virtually all environmental media at trace concentrations, including rocks, soils, water, and living organisms. Anthropogenic activities, such as irrigating seleniferous soils, coal and phosphorus mining, operation of coal-fired power plants, and oil refining, have increased Se beyond background concentrations in many aquatic ecosystems (Lemly 1997).

Given the role of Se as an essential micronutrient, aquatic organisms readily bioaccumulate organic forms of Se (e.g., selenomethionine), yet frequently are not able to excrete Se at the same rate of consumption at elevated concentrations. This imbalance of intake and excretion can lead to elevated tissue concentrations that can be toxic to the organism. Direct toxic effects have been measured in adult organisms via decreased survival or growth and in young by decreased survival, growth, or increased occurrences of larval deformities (together, considered measures of reproductive success). The margin between required concentrations and those that may become toxic is narrow; perhaps as low as one order of magnitude for some vertebrate species, and highly variable within and between species. Furthermore, it has been difficult to differentiate the toxicity of different species of Se that occur due to varying hydrological and redox (reduction-oxidation) conditions (Payne et al. 2013).

While the EPA is in the process of updating the national criteria for Se, it is unknown when a new draft document will be released. The release date has been delayed multiple times over the last several years, and the EPA has not publicly provided a new estimated release date. Therefore, in the meantime, interested states may develop their own updated criteria instead of relying on EPA's outdated and inappropriate criteria from 1987.

Regardless of when a new EPA criteria document may become available, derivation of an updated Se standard for an individual state is scientifically defensible, using approaches and analyses provided herein, due to new acute water-column toxicity and tissue-based chronic toxicity data made available since the current criterion (EPA 1987) and the last draft criterion (EPA 2004) were released. This document provides a review of available toxicity data for Se on aquatic life, with emphasis on fish. These data allow derivation of updated acute water column-based Se criteria and chronic fish tissue-based criteria.

2.0 Summary of Existing Criteria

2.1 National Ambient Water Quality Criteria for Selenium

The first national ambient water quality criteria (AWQC) for Se for the protection of aquatic life were published in 1976 (EPA 1976), updated in 1980 (EPA 1980), and then partially updated in 1987, 1995, and 1996 (EPA 1987 and 1995). These criteria were recommendations of water column limits for Se for the protection of aquatic life as required in the Clean Water Act (CWA). Under Section 304(a) of the CWA, the EPA must also periodically revise AWQC to incorporate the latest scientific knowledge on the kind and extent of all identifiable effects of pollutants on aquatic communities and human health. National AWQC are recommendations to states that must adopt water quality standards. Respective criteria can be modified to best reflect each state's unique aquatic communities and environmental conditions.

The current acute (CMC) national AWQC (EPA 2012) for Se is:

$$CMC = \frac{1}{[f1/CMC1) + (f2/CMC2)]}$$

where f1 and f2 are the fraction of total Se that are comprised as selenite (Se^{+4}) and selenate (Se^{+6}), respectively, and CMC1 and CMC2 (acute values) are 185.9 and 12.82 micrograms per liter (µg/L), respectively, based on acute toxicity data and calculations from the 1987 criteria document (EPA 2012). The current chronic national AWQC for Se is 5 µg/L.

In 2002 and later in 2004, the EPA published draft criteria documents that recognize the differential modes of Se toxicity – primarily water column exposure for acute toxicity and mixed water column and dietary exposure followed by bioaccumulation into tissues for chronic (Canton 1999, Brix et al. 2001a,b, EPA 2002 and 2004). The document also acknowledged the different acute toxicity of selenite and selenate and the relationship between selenate toxicity and ambient sulfate concentration (EPA 2004). Se speciation is important in determining potential exposure routes and biogeochemical cycling in aquatic environments (Ralston et al. 2008). Elemental Se and most metallic selenides have relatively low toxicities because of their low bioavailability. By contrast, selenate and selenite are very bioavailable. At pH values below 7.0, selenites are rapidly reduced to elemental Se under mildly reducing conditions (Faust and Aly 1981) that are common in most aquatic sediments. Selenate usually predominates in well-aerated surface waters, especially those with alkaline conditions (Faust and Aly 1981, Luoma et al. 1992). Selenite is more reactive than selenate because of its polarity and high attraction to other molecules (EPA 2004), making selenite more bioavailable, increasing exposure and potential toxicity to aquatic organisms.

The EPA (2004, 2012) derived two separate acute criteria for selenite and selenate. The draft selenite criterion (258 µg/L) was derived using the established 5th percentile criteria

derivation methodology (Stephan et al. 1985) based on an updated selenite acute toxicity database. The selenate criterion was derived using the same 5th percentile methodology on an updated acute toxicity database. Additionally, the acute selenate values were normalized based on sulfate concentrations in the test, as data indicate sulfate has a significant influence on selenate acute toxicity (Brix et al. 2001a,b, EPA 2004). The result is a sulfate-based acute toxicity water quality criteria equation for selenate:

$$Acute\ selenate = e^{(0.5812[ln\ (sulfate)] + 3.357)}$$

Chronic Se toxicity, on the other hand, is related to dietary exposure and bioaccumulative properties of Se in aquatic biota rather than water column concentrations. Therefore, the draft criteria document (EPA 2004) proposed a national tissue-based chronic criterion. Fish are considered particularly sensitive to chronic Se exposure (Coyle et al. 1993, GEI et al. 2008, Hamilton et al. 1990, Hermanutz et al. 1996), with early life history stages of fish development being most affected. Due to the bioaccumulative properties of Se, exposure routes in embryonic and larval fish can be from maternally derived yolk absorption or directly from the environment. Selective early life stage sensitivities in fish can create a scenario where significant population mortality occurs in Se affected waters, despite the presence of seemingly healthy adult populations (Lemly 2002).

Twenty-four studies were critically evaluated in the draft Se criteria document (EPA 2004) resulting in Se tissue thresholds for nine species in seven genera, along with one general family tissue threshold. After their evaluation of all acceptable studies, the EPA proposed the chronic criterion of 7.9 micrograms per gram (µg/g) Se whole body (wb) dry weight (dw), which was the value derived from a single study that investigated juvenile bluegill mortality during winter months (Lemly 1993). Although it is acceptable to default to a particularly important test result based on EPA ambient water quality criteria guidelines (Stephan et al. 1985; aka *1985 Guidelines*), criteria are more commonly derived from a 5th percentile calculation of the entire dataset, taking into account the relative sensitivity of all species represented in a dataset containing a minimum of eight specific families. Alternatively, a criterion may be set to the most sensitive species or genus mean value, both of which are mean values derived from multiple studies. However, the application of a chronic tissue criterion based on a single study of one species' Se sensitivity may not be applicable to all species or to aquatic environments that do not contain that species (i.e., bluegill) or species with similar sensitivities to Se. As such, we are recommending a more formal evaluation of available chronic data, with more explicit use of the 1985 Guidelines.

2.2 Virginia State Surface Water Quality Standards

Virginia's current surface water quality standards are presented in Virginia Administrative Code 9VAC25-260-140 (VDEQ 2011). The acute and chronic Se standards for the protection of aquatic life, based on the EPA's 1987 criteria (EPA 1987), are 20 µg/L and 5 µg/L total recoverable Se, respectively.

3.0 Updates to Virginia State Se Standards

While EPA is in the process of updating the national Se criteria, interested states would benefit from developing their own updated criteria and not relying on the outdated and inappropriate criteria from the 1987 criteria document – now over 25 years old.

The current draft Se AWQC document (EPA 2004) provides a relatively up-to-date and scientifically defensible dataset for the development of updated acute and chronic Se standards for Virginia. Additional chronic tissue-based data published since 2004 are also available. Acute criteria updates from the 2004 draft and all available chronic data from both the 2004 draft and newly published studies were compiled into a Se chronic toxicity database for our evaluation.

3.1 Acute Se

The proposed acute freshwater criteria in the 2004 AWQC draft document are greatly improved and represent a significant increase from the current Virginia acute total Se standard of 20 µg/L. Virginia water quality criteria for total Se cannot differentiate between the markedly different reported selenate and selenite toxicity. Substantial improvements over current criteria include:

1. recognition of the differential modes of toxicity between acute (water column) and chronic (dietary and bioaccumulation) Se exposure (Canton 1999),
2. developing the relationship between selenate toxicity and sulfate concentration (Brix et al. 2001a, b), and
3. development of separate acute criteria for selenite and selenate.

Given the considerable difference in the acute Se criteria values proposed by the EPA in the 2004 draft Se AWQC document (EPA 2004) compared to their previous criteria (EPA 1987), there is substantial evidence that the current Virginia acute standard of 20 µg/L is not relevant and adoption of updated acute standards is warranted. EPA's updated draft acute Se criteria for selenite and selenate would provide a strong, scientifically defensible update to acute Se standards for Virginia.

Based on this analysis, we would strongly recommended acute Se standards for Virginia be replaced with the current acute (CMC) national AWQC (EPA 2012) equation for total Se and that the values for selenite and selenate currently based on the 1987 criteria document (EPA 1987) be replaced with the more scientifically-defensible values from the 2004 draft:

$$CMC = \frac{1}{[f1/CMC1) + (f2/CMC2)]}$$

where f1 and f2 are again the fraction of total Se that are comprised as selenite (Se^{+4}) and selenate (Se^{+6}), respectively, and CMC1 and CMC2 are now 258 µg/L for selenite and the equation $e^{(0.5812[\ln(\text{sulfate})]+3.357)}$ for selenate (EPA 2004). It is understood that many water quality programs do not include monitoring of the various species of Se. Thus, if Se speciation analyses are not conducted on water column Se samples, we would recommend use of the more restrictive of the two values, 258 µg/L, as a conservative acute total Se standard, assuming sulfate concentrations greater than approximately 44 mg/L. If sulfate values are less than approximately 44 mg/L (Table 1), then speciation may be warranted to develop acute standards that are fully protective, as this equation may result in values lower than 258 µg/L.

Table 1: Freshwater selenate values (µg/L dissolved) for varying concentrations of sulfate.

	Mean Sulfate (mg/L)									
	5	10	15	20	25	30	35	40	45	50
Selenate (acute)	73	109	138	164	186	207	227	245	262	279

3.2 Chronic Se

As discussed above (Section 2.1), the EPA supports a tissue-based criterion for Se in its draft document (EPA 2004) because it incorporates site-specific factors such as chemical speciation and rates of transformation, variations in temporal concentrations in water, types of organisms constituting the food chain, and variable rates of exchange between water, sediment, and organisms.

Prior to proposing a water quality standard using tissue-based criteria, evaluation of EPA's 2004 draft criterion was necessary. We evaluated the available chronic toxicity Se tissue data at the family level specific to the families of fish that occur (or would be expected to occur) in Virginia waters (VDGIF 2013). The most species-rich families in Virginia include Percidae, Centrarchidae, Cyprinidae, Catostomidae, and Ictaluridae. The 2004 draft criteria document (EPA 2004) only included chronic tissue endpoints for three of these families: Centrarchidae, Cyprinidae, and Catostomidae. However, since 2004, additional data have become available, including data for these and other species that occur in Virginia.

Updates to the chronic Se criterion that occurred as part of the 2004 draft document (EPA 2004) as well as new data that have become available after that document are discussed below. Specifically, GEI was provided a table from EPA (Charles Delos, personal communication, October 5, 2011) that listed fish species and references that EPA will be using, at least as of that date, in the pending updated criteria document. EPA did not provide their calculations of chronic effect concentrations for those studies. Therefore, as part of the analysis below, we acquired the references EPA provided and evaluated the data, including conducting calculations of chronic values such as no-effect concentrations (NOEC), low-effect concentrations (LOEC), and EC_{10} (point estimate of effect concentration at the 10% level), as appropriate. In addition, data summaries by Ohlendorf (2008), GEI et al. (2008),

DeForest and Adams (2011), and DeForest et al. (2012) were evaluated to ensure our database was complete.

In addition, it is our understanding that a new tissue-based criterion would be focused on the reproductive tissues, represented by egg/ovary tissue. The 2004 draft was based on whole-body tissue. In either case, data must be translated to allow use of as many data points from as many studies as possible. Therefore, in our analysis, we converted data from studies using only whole-body tissues to their equivalent egg/ovary values and vice versa, based on equations provided in EPA (2004; for bluegill), GEI (2008; for fathead minnow), and GEI et al. (2008; for bluegill, cutthroat trout, and both species combined to derive an "all species" equation).

Additionally, because only bluegill and cutthroat trout data were used to derive the "all species" equation in GEI et al. (2008), we further updated the "all species" equation to include the fathead minnow data from GEI (2008; Appendix A), along with the data for bluegill and cutthroat trout.

These equations allowed derivation of a chronic Se criterion based on either egg/ovary or whole-body tissue data for all appropriate studies and fish species. We believe this inclusion of whole-body tissue thresholds, in addition to egg/ovary thresholds, will be helpful in the implementation of a tissue-based criterion, given the difficulties of field-collection of egg/ovary tissue.

3.2.1 Calculating Tissue Thresholds

In order to develop a tissue-based chronic criterion, EPA considered and critically evaluated available tissue-based studies (EPA 2004). After their evaluation, EPA proposed the chronic criterion of 7.9 µg/g wb dw, which is based on a single bluegill study conducted by Lemly (1993). However, a considerable amount of additional data for bluegills and other species are available. The method of basing a criterion on a single study is not consistent with EPA criteria development methods (Stephan et al. 1985), which typically utilize an EC_{10} or EC_{20} from multiple studies on multiple species (e.g., EPA 2009, 2004, 1999). While the draft EPA Se criteria document (EPA 2004) recommends use of EC_{20}s, we have decided to use EC_{10}s to derive a recommended tissue-based chronic water quality criterion for Virginia, which is more conservative and consistent with other recent approaches (e.g., DeForest and Adams 2011), as well as consistent with expected calculations in the pending EPA updated Se criteria document (Charles Delos, EPA, personal communication, November 16, 2012).

Several prior studies have summarized a number of Se-effects values from studies with a variety of coldwater and warmwater fish, including some non-species-specific values from synthesis papers (Ohlendorf 2008, DeForest and Adams 2011, DeForest et al. 2012). The DeForest and Adams (2011) analysis included some recalculation of endpoints and new calculations of previously unreported endpoints, such as EC_{10} and EC_{20} values, which the

original researcher may not have calculated. We evaluated these summaries and added additional data from other available studies either not cited or not available at the time these studies were published.

Much of the available Se toxicity data are for species not expected to be found (either the actual species or species for which the test organism may have served as a surrogate) in Virginia (e.g., Chinook salmon, and Yellowstone cutthroat trout; see Table 2 below). Thus, these data were not considered relevant to Virginia and were not carried forward in the analysis. In addition, several data points were not carried forward because they were reported as general tissue thresholds based on summaries of data from other studies (i.e., "synthesis" studies). Because the reported "synthesis-thresholds" were not specifically tied to an individual species, tissue type, or known test conditions, they are not appropriate for use in deriving a chronic criterion. In addition, many of the studies used below are included in those synthesis-threshold papers. A number of additional "rules" were established for evaluation of data prior to derivation of a revised chronic criterion and applied, as possible, given available data.

- Tests using only aqueous Se exposure were excluded because such tests are environmentally irrelevant due to the importance of dietary exposure for evaluation of Se toxicity (GEI et al. 2008; DeForest and Adams 2011).
- Although EPA used EC_{20} Se toxicity data when possible (EPA 2004), we utilized EC_{10} values when available to be more conservative and consistent with recent approaches (DeForest and Adams 2011).
- In cases where both egg and ovary data were available for a study, the geometric mean of the two values was used to calculate the chronic value for egg/ovary tissue.

As described below, studies which reported toxicity data were reviewed to ensure the values were appropriate for further use in deriving updated chronic criterion. During our review we found studies that were considered relevant and usable, as well as a number of papers that were not as relevant or usable. Studies that were not considered for further evaluation included those with potential issues with study methods that made the data unusable or studies irrelevant for species expected to be found in Virginia. Specific discussion of species' data and decisions on studies/data usage are summarized below to provide better documentation of our decisions following implementation of these data usage rules. Additional summary information about these studies is available in DeForest and Adams (2011).

Relevant and usable Se toxicity data for species expected to be found or which may serve as surrogate species (e.g., white sturgeon) for Virginia fish communities were summarized by genus and analyzed tissue type (Table 3). These data were used to calculate genus mean chronic values (GMCV), which were then ranked from least to most sensitive for both whole-body and egg/ovary values (Table 3), consistent with the 1985 Guidelines.

Table 2: Freshwater selenium data from chronic toxicity tests. Bold shaded values were carried over to Table 3.

Species	Reference	Notes	Test Type	Toxicological Endpoint	Chronic Value mg/kg dw[a]	Usable/ Relevant
Egg/Ovary Data						
Pimephales promelas Fathead minnow	Schultz and Hermanutz 1990	EPA 2004 used 85% moisture for ovaries for this study	Dietary and waterborne (mesocosm - Monticello)	LOAEC for larval edema and lordosis	**Ovary LOAEC: <39.27**	Y
Fathead minnow	Ogle and Knight 1989		Lab	NOEC for reproduction	Ovary NOEC: >10.92	N
Fathead minnow	GEI 2008	Translated from WB using GEI 2008 FHM equation	Dietary and waterborne (field Denver, CO)	EC_{10} larval skeletal and edema abnormality CV for larval deformities	**Egg/Ovary EC_{10}: 45** Egg/Ovary CV: 53.8	Y
Fathead minnow	Bennett et al. 1986	Translated from WB using GEI 2008 FHM equation	Dietary	LOEC for growth	Ovary LOEC: <57.75	N
Fathead minnow	Bertram and Brooks 1986	Translated from WB using GEI 2008 FHM equation	Dietary	NOEC for growth	Ovary NOEC: >3.94	N
Fathead minnow	Dobbs et al. 1996	Translated from WB using GEI 2008 FHM equation	Dietary	LOEC for growth	Ovary LOEC: <63.68 -<101.27	N
Oncorhynchus mykiss Rainbow trout	Holm 2000; Holm et al. 2003; Holm et al. 2005; EC_{10} and EC_{20} values calculated by DeForest and Adams 2011	Values from DeForest and Adams	Dietary and waterborne (field Luscar River, Alberta)	EC_{10} for skeletal deformities EC_{20} for skeletal deformities	Egg NOEC: 17 Egg LOEC: 25 **Egg EC_{10}: 23** Egg EC_{20}: 27	Y
Oncorhynchus clarki bouvieri Yellowstone cutthroat trout	Hardy et al. 2010		Lab	NOEC for larval deformities, mortality	Egg NOEC: >16.04	N
Yellowstone cutthroat trout	Formation Environmental 2011		Field	MATC for alevin mortality	Egg MATC: 25	N
Oncorhynchus clarki Cutthroat trout	Hardy 2005		Dietary (lab)	NOAEC for embryo/larval deformities	Egg NOAEC: >16-18.0 ± 1.41	N
Oncorhynchus clarki lewisi Westslope cutthroat trout	Kennedy et al. 2000		Dietary and waterborne (field - Fording River, BC)	NOAEC for embryo/larval deformities and mortality	Egg NOAEC: >21.0 ± 18.3	N
Westslope cutthroat trout	Nautilus Environmental 2011		Field	EC_{10} for alevin mortality	Egg EC_{10}: 24.8	N
Westslope cutthroat trout	Rudolph et al. 2008; EC_{10} and EC_{20} values calculated by DeForest and Adams 2011	NOEC and LOEC for larval deformities; EC_{10} and EC_{20} for alevin mortality	Dietary and waterborne (field - Clode Pond, BC); No Se-related deformities; next	NOEC for larval edema LOEC for larval edema EC_{10} for alevin mortality EC_{20} for alevin mortality	Egg NOEC: 20.6 Egg LOEC: 46.8 Egg EC_{10}: 17 Egg EC_{20}: 23	N

Species	Reference	Notes	Test Type	Toxicological Endpoint	Chronic Value mg/kg dw[a]	Usable/ Relevant
			highest [Se] tested (46.6 µg/g dw) did not produce viable fry			
Salvelinus fontinalis Brook trout	Holm 2002; Holm et al. 2003; Holm et al. 2005	CV for craniofacial deformities, calc assuming 75.84% moisture from Holm 2002. Egg NOAEC given in Holm 2003 (6mg/kg egg ww) for rainbow trout.	Dietary and waterborne (field Luscar River, Alberta)	combined 2000/2001 studies: NOEC for craniofacial deformities; NOEC = >20; EC_{06} = 20	**Egg NOEC: >20**	Y
Salvelinus malma Dolly Varden	Golder 2009		Dietary and waterborne (field Kemess Mine NW BC)	EC_{10} for total deformities EC_{20} for total deformities	Egg EC_{10}: 54 Egg EC_{20}: 60	N
Salmo trutta Brown trout	NewFields 2009		Dietary and waterborne (field)	EC_{10} for larval survival EC_{20} for larval survival EC_{10} for larval deformities EC_{20} for larval deformities	Egg EC_{10}: 20.8 Egg EC_{20}: 23.1 **Egg EC_{10}: 22** Egg EC_{20}: 23.4	Y
Xyrauchen texanus Razorback sucker	Hamilton et al. 2005a, 2005b	Larval deformities	Field	NOEC for larval deformities LOEC for larval deformities MATC for larval deformities	Egg LOEC: 37.8 Egg NOEC: 46.5 Egg MATC: 41.9	N
Catostomus commersonii White sucker	de Rosemond et al. 2005	Larval deformities	Field	EC_{13} for larval deformities	**Egg EC_{13}: 25.6**	Y
Lepomis macrochirus Bluegill	EPA 2004; from Lemly 1993	Translated from WB using bluegill equation in GEI et al. 2008	Lab	LOEC for mortality at 4°C	**Ovary LOEC: 17.01** Ovary LOEC: 12.59	Y
Bluegill	Bryson et al. 1984		Dietary and waterborne (field - Hyco Reservoir, NC)	LOAEC for larval mortality	Ovary LOAEC: <49	N
Bluegill	Bryson et al. 1985a	Represents mean of 4 females from Hyco reservoir	Dietary and waterborne (field - Hyco Reservoir, NC)	Chronic value for swim-up larvae	Ovary CV: <30 ±3.4	N
Bluegill	Bryson et al. 1985b		Field	NOEC for hatchability, swim-up LOEC for hatchability,	Ovary NOEC: >14.8 Ovary LOEC: >9.2	N

Species	Reference	Notes	Test Type	Toxicological Endpoint	Chronic Value mg/kg dw[a]	Usable/ Relevant
				swim-up		
Bluegill	Gillespie and Baumann 1986		Dietary and waterborne (field - Hyco Reservoir, NC)	Chronic value for larval survival	Ovary CV: <38.6	N
Bluegill	Doroshov et al. 1992; EC_{10} and EC_{20} values calculated by DeForest and Adams 2011	Geometric mean of ovary and egg EC_{10}s = **18.33**	Dietary (lab)	NOEC for larval edema LOEC for larval edema EC_{10} for larval edema EC_{20} for larval edema	Ovary NOEC: 3.94 Ovary LOEC: 21.10 **Ovary EC_{10}: 16** Ovary EC_{20}: 20 Egg NOEC: 8.55 Egg LOEC: 25.81 **Egg EC_{10}: 21** Egg EC_{20}: 23	Y
Bluegill	Coyle et al. 1993; EC_{10} and EC_{20} values calculated by DeForest and Adams 2011	Wb, ovary, and egg NOECs, LOECs, EC_{10}s, and EC_{20}s for larval mortality; geometric mean of ovary and egg EC_{10}s = **23**	Dietary and waterborne (lab)	NOEC for larval survival LOEC for larval survival EC_{10} for larval survival EC_{20} for larval survival	WB NOEC: 7 WB LOEC: 16 WB EC_{10}: 8 WB EC_{20}: 8.5 Ovary NOEC: 20 Ovary LOEC: 35 **Ovary EC_{10}: 24** Ovary EC_{20}: 27 Egg NOEC: 22.5 Egg LOEC: 41.3 **Egg EC_{10}: 22** Egg EC_{20}: 26	Y
Bluegill	Hermanutz et al. 1992; Hermanutz et al. 1996; EC_{10} and EC_{20} values calculated by DeForest and Adams 2011		Dietary and waterborne (mesocosm - Monticello)	NOEC for larval edema LOEC for larval edema EC_{10} for larval edema EC_{20} for larval edema	WB NOEC: 4.4 WB LOEC: 21.8 WB EC_{10}: 7.7 WB EC_{20}:9.7 Ovary NOEC: 17.3 Ovary LOEC: 69 **Ovary EC_{10}: 30** Ovary EC_{20}: 36	Y
		Back-calc ovaries from EPA 2004 criteria value given for parent tissue (17.35) using bluegill equation in GEI et al. (2008)	Dietary (mesocosm - Monticello)	NOAEC for larval survival, edema, lordosis and hemorrhaging	Ovary NOAEC: >36.8	N
Bluegill	WVDEP 2010	No measure of toxicity; egg [Se] only from 2009 (max sample 13.8% deform, avg 5.38%). Some spp had egg [Se], but only larval deformity data for bluegill. Eggs for	Dietary and waterborne (field, Upper Mud River, WV)	NOAEC for larval deformities	Egg NOAEC: <9.8	N

Species	Reference	Notes	Test Type	Toxicological Endpoint	Chronic Value mg/kg dw[a]	Usable/ Relevant
		deformity studies not from same females that had eggs excised so egg [Se] are not truly indicative of reproductive impairment.				
Bluegill	McIntyre et al. 2008	Translated from WB using bluegill equation in GEI et al. 2008	Dietary	EC_{10} for mortality at 4°C EC_{20} for mortality at 4°C EC_{10} for mortality at 9°C EC_{20} for mortality at 9°C	**Ovary EC_{10}: 18.3** Ovary EC_{20}: 19.8 **Ovary EC_{10}: 28.6** Ovary EC_{20}: 30.8	Y
Micropterus salmoides Largemouth bass	CP&L 1997	Maternal transfer	Lab	EC_{10} for larval mortality EC_{20} for larval mortality	**Ovary EC_{10}: 22** Ovary EC_{20}: 24	Y
Esox lucius Northern pike	Muscatello et al. 2006		Dietary and waterborne (field Saskatoon, Sask.)	NOEC larval deformities LOEC larval deformities EC_{10} larval deformities EC_{20} larval deformities	Egg NOEC: 3.8 Egg LOEC: 31.3 **Egg EC_{10}: 20.4** Egg EC_{20}: 33.6	Y
Gambusia holbrooki Eastern mosquitofish	Staub et al. 2004	Translated from WB using updated "all species" equation derived by GEI, see Appendix A	Field MT	NOEC for brood size/offspring viability	**Egg NOEC: >22.6**	Y
Gambusia affinis Western mosquitofish	Saiki et al. 2004	Translated from WB using updated "all species" equation derived by GEI, see Appendix A	Field MT	NOEC for fry mortality and deformities	Egg NOEC: >37.2	N
Acipenser transmontanus White sturgeon	Tashjian et al. 2006	Translated from WB using updated "all species" equation derived by GEI, see Appendix A	Dietary	NOECs, LOECs, EC_{10}s, and EC_{20}s for growth	**Egg EC_{10}: 30.6** Egg EC_{20}: 52.7	Y
White sturgeon	Linville 2006	Maternal transfer	Lab	EC_{10} larval skeletal and edema abnormality	**Egg EC_{10}: 15.3**	Y
Whole-body Data						
Fathead minnow	Schultz and Hermanutz 1990	EPA 2004 used 85% moisture for ovaries for this study; translated from ovary using GEI 2008 FHM equation	Dietary and waterborne (mesocosm - Monticello)	LOAEC for larval edema and lordosis	**WB LOAEC: <28.99**	Y
Fathead minnow	Ogle and Knight 1989		Lab MT	NOEC for reproduction	WB NOEC: >7.5 Ovary NOEC: >10.92	N
Fathead minnow	GEI 2008		Dietary and waterborne (field Denver, CO)	EC_{10} larval skeletal and edema abnormality CV larval deformities	**WB EC_{10}: 33** WB CV: 40	Y
Fathead minnow	Bennett et al. 1986		Dietary	LOEC for growth	WB LOEC: <43.0	N
Fathead minnow	Bertram and Brooks 1986		Dietary	NOEC for growth	WB NOEC: >2.2	N
Fathead minnow	Dobbs et al. 1996		Dietary	LOEC for growth	WB LOEC: <47.5 - <76.0	N

Species	Reference	Notes	Test Type	Toxicological Endpoint	Chronic Value mg/kg dw[a]	Usable/ Relevant
Rainbow trout	Hodson et al. 1980	Exposed to [selenite] 5.5-53 µg/L; only measured tissue in 53 µg/L treatment; negligible effects in 53 µg/L treatment; water-only exposure to inorganic Se not environmentally relevant; not used by DeForest and Adams	Aqueous exposure		WB: >1.8	N
Rainbow trout	Hunn et al. 1987	Not used by DeForest and Adams because exposed to mixture of elevated elements and water-only exposure to inorganic Se not environmentally relevant	Aqueous exposure	NOEC LOEC	WB: 2.6 WB: 4.3	N
Rainbow trout	Holm 2000; Holm et al. 2003; Holm et al. 2005; EC_{10} and EC_{20} values calculated by DeForest and Adams 2011	Translated from egg using trout equation in GEI et al. 2008	Dietary and waterborne (field Luscar River, Alberta)	EC_{10} for skeletal deformities EC_{20} for skeletal deformities	WB NOEC: 9.18 WB LOEC: 12.26 **WB EC_{10}: 11.52** WB EC_{20}: 12.99	Y
Cutthroat trout	Hardy 2005	Translated from egg using trout equation in GEI et al. 2008	Dietary (lab)	NOAEC for embryo/larval deformities	WB NOAEC: >8.77-9.58	N
Brook trout	Holm 2002; Holm et al. 2003; Holm et al. 2005	CV for craniofacial deformities, calc assuming 75.84% moisture from Holm 2002. Egg NOAEC given in Holm 2003 (6mg/kg egg ww) but only for rainbow trout; Translated from egg using trout equation in GEI et al. 2008	Dietary and waterborne (field Luscar River, Alberta)	NOEC for craniofacial deformities; NOEC >20; EC_{06} = 20	**WB NOEC: >10.34**	Y
Brown trout	NewFields 2009	Translated from egg using trout equation in GEI et al. 2008	Dietary and waterborne (field)	EC_{10} for larval survival EC_{20} for larval survival EC_{10} for larval deformities EC_{20} for larval deformities	WB EC_{10}: 10.68 WB EC_{20}: 11.55 **WB EC_{10}: 11.14** WB EC_{20}: 11.67	Y
White sucker	de Rosemond et al. 2005	Translated from WB using updated "all species" equation derived by GEI, see Appendix A	Field	EC_{13} for larval deformities	**WB EC_{13}: 13.05**	Y
Bluegill	EPA 2004; from Lemly 1993	Draft criterion; 40% overwinter mortality in juveniles (winter stress)	Lab	LOEC for mortality at 4°C	**WB: 7.91** WB: 5.85	Y
Bluegill	Cleveland et al. 1993	Water-only exposure to inorganic Se is not environmentally relevant; not used by DeForest and Adams	Aqueous exposure	NOEC for mortality LOEC for mortality	WB NOEC: 3.8 WB LOEC: 5.0	N
Bluegill	McIntyre et al. 2008	Mortality (winter stress syndrome); EC_{10} and EC_{20} at 4°C and 9°C	Dietary	EC_{10} for mortality at 4°C EC_{20} for mortality at 4°C EC_{10} for mortality at 9°C EC_{20} for mortality at 9°C	**WB EC_{10}: 9.56** WB EC_{20}: 10.16 **WB EC_{10}: 13.29** WB EC_{20}: 14.02	Y
Bluegill	Coyle et al. 1993; EC_{10} and EC_{20}	Wb, ovary, and egg NOECs, LOECs,	Dietary and	NOEC for larval survival	WB NOEC: 7	Y

Species	Reference	Notes	Test Type	Toxicological Endpoint	Chronic Value mg/kg dw[a]	Usable/ Relevant
	values calculated by DeForest and Adams 2011	EC_{10}s, and EC_{20}s for larval mortality	waterborne (lab)	LOEC for larval survival EC_{10} for larval survival EC_{20} for larval survival	WB LOEC: 16 **WB EC_{10}: 8** WB EC_{20}: 8.5 Ovary NOEC: 20 Ovary LOEC: 35 Ovary EC_{10}: 24 Ovary EC_{20}: 27 Egg NOEC: 22.5 Egg LOEC: 41.3 Egg EC_{10}: 22 Egg EC_{20}: 26	
Bluegill	Hermanutz et al. 1992; Hermanutz et al. 1996; EC_{10} and EC_{20} values calculated by DeForest and Adams 2011		Dietary and waterborne (mesocosm - Monticello)	NOEC for larval edema LOEC for larval edema EC_{10} for larval edema EC_{20} for larval edema	WB NOEC: 4.4 WB LOEC: 21.8 **WB EC_{10}: 7.7** WB EC_{20}:9.7 Ovary NOEC: 17.3 Ovary LOEC: 69 Ovary EC_{10}: 30 Ovary EC_{20}: 36	Y
Bluegill	Bryson et al. 1984	Translated from ovary using bluegill equation in GEI et al. 2008	Dietary and waterborne (field - Hyco Reservoir, NC)	LOAEC for larval mortality	WB CV: <19.67	N
Bluegill	Bryson et al. 1985a	Represents mean of 4 females from Hyco reservoir. Translated from ovary using bluegill equation in GEI et al. 2008	Dietary and waterborne (field - Hyco Reservoir, NC)	Chronic value for swim-up larvae	WB CV: <13.75	N
Bluegill	Bryson et al. 1985b	Translated from ovary using bluegill equation in GEI et al. 2008	Field	NOEC for hatchability, swim-up LOEC for hatchability, swim-up	WB NOEC: >8.21 WB LOEC: >5.80	N
Bluegill	Gillespie and Baumann 1986	Translated from ovary using bluegill equation in GEI et al. 2008	Dietary and waterborne (field - Hyco Reservoir, NC)	Chronic value for larval survival	WB CV: <16.53	N
Bluegill	Doroshov et al. 1992; EC_{10} and EC_{20} values calculated by DeForest and Adams 2011	Translated from ovary or egg using bluegill equations in GEI et al. 2008 (geometric mean of translated ovary and egg values was calc.)	Dietary (lab)	NOEC for larval edema LOEC for larval edema EC_{10} for larval edema EC_{20} for larval edema	WB NOEC: 3.25 WB LOEC: 9.85 **WB EC_{10}: 8.12** WB EC_{20}: 9.17	Y

Species	Reference	Notes	Test Type	Toxicological Endpoint	Chronic Value mg/kg dw[a]	Usable/ Relevant
Largemouth bass	CP&L 1997	Maternal transfer; Translated from ovary using bluegill equation in GEI et al. 2008	Lab	EC_{10} for larval mortality EC_{20} for larval mortality	**WB EC_{10}: 10.96** WB EC_{20}: 11.68	Y
Northern pike	Muscatello et al. 2006	Translated from egg using updated "all species" equation derived by GEI, see Appendix A	Dietary and waterborne (field Saskatoon, Sask.)	EC_{10} larval deformities EC_{20} larval deformities	**WB EC_{10}: 10.92** WB EC_{20}: 16.16	Y
Eastern mosquitofish	Staub et al. 2004		Field MT	NOEC for brood size/offspring viability	**WB: >11.85**	Y
Western mosquitofish	Saiki et al. 2004		Field MT	NOEC for fry mortality and deformities	WB: >17.5	N
White sturgeon	Tashjian et al. 2006		Dietary	NOECs, LOECs, EC_{10}s, and EC_{20}s for growth	WB NOEC: 14.7 WB LOEC: 22.5 **WB EC_{10}: 15** WB EC_{20}: 23	Y
White sturgeon	Linville 2006	Maternal transfer; Translated from egg using updated "all species" equation derived by GEI, see Appendix A	Lab	EC_{10} larval skeletal and edema abnormality	**WB EC_{10}: 8.71**	Y
Other Data (E.g., Synthesis Studies)						
Various species	Lemly 1996	Reproductive failure	Synthesis	Reproductive failure	Egg: 10	N
Cold FW fish	Chapman 2007	Range in "effects thresholds" for coldwater species	Synthesis		Egg: >16–40	N
Bluegill and fathead minnow	DeForest and Adams 2011	EC_{10} for larval mortality and edema	Synthesis		Ovary EC_{10}: 17	N
Various species	Lemly 1996	Reproductive failure	Synthesis		Ovary: 10	N
Bluegill and fathead minnow	DeForest and Adams 2011		Synthesis	EC_{10} for larval mortality and edema	WB EC_{10}: 8.1	N
Various species	Hamilton 2002; Lemly 1996		Synthesis	Juvenile mortality and reproductive failure	WB: 4	N
Chinook salmon	Hamilton et al. 1990; Hamilton 2002, 2003		Lab and synthesis	Swim-up larval growth and survival	WB: 4–6.5	N
Rainbow trout, Brook trout	Holm et al. 2003	Rapid rise in edema and deformities in fry (parental exposure); Egg (52% moisture); Muscle translation	Field (eggs/milt) Lab (fish rearing)	Larval edema/deformities	Egg: 12.5 Muscle: 4.3	N
Rainbow trout	Holm et al. 2005 from Chapman 2007	Threshold between 8–10 µg/g ww; converted to dw using 75% moisture	Field		Egg: 32–40	N
Rainbow trout	Vidal et al. 2005	NOEC and LOEC could not be identified because dose-response data anomalous	Dietary	NOEC and LOEC for larval deformities	WB NA	N
Brook trout	Holm et al. 2005 from Chapman 2007	No increase in larval deformities at 6.6 and 7.8 µg/g ww; converted to dw using 75% moisture	Field	Larval deformities	Egg: >26.4–31.2	N

Species	Reference	Notes	Test Type	Toxicological Endpoint	Chronic Value mg/kg dw[a]	Usable/ Relevant
Bluegill	Cleveland et al. 1993	NOEC and LOEC could not be identified because dose-response data anomalous	Dietary	NOEC and LOEC for mortality	WB NA	N
Various species	USDI 1998 from various studies	Background; no risk to aquatic life	Synthesis		WB: <4	N
Various species	Engberg et al. 1998	Range of concern	Synthesis		WB: 4–12	N
Various species	Lemly 2002	Max allowable [Se]; values are recommendations by Lemly based on synthesis and interpretation of literature cited	Synthesis	Protective of reproduction	WB: 4 Muscle: 8 Liver: 12 Egg: 10	N
Centrarchids, Fathead minnows, Salmonids, Percichthyids	Lemly 1998; cited Hoffman et al. 1988, Lemly 1985a, 1993b,c, 1997b,c, Ohlendorf 1989, Ohlendorf et al. 1986a,b, 1988, Skorupa and Ohlendorf 1991, Skorupa et al. 1996	Diagnostic residues for reproductive impairment	Synthesis	Larval/fry deformity or mortality	WB: 5–7 Muscle: 6–8 Liver: 15–20 Egg: 5–10 Larvae/Fry: 8–12	N
Perch and Bluegill	USDI 1998; 4–6 has Marginal Risk in Presser et al. 2004	Reproductive impairment in sensitive species	Synthesis	EC_{10} for reproductive impairment	WB: 4–6 Gonad/Egg: 7–13	N
Various species	DeForest et al. 1999	Recommended toxicity guidelines	Synthesis	EC_{10} for toxicity	WB: 6 (coldwater) WB: 9 (warmwater) Ovary: 17	N
Centrarchids	Lemly 1993	Rapid rise in deformities (terata)	Synthesis	Deformities	Egg: 10 Egg: 6–17	N
Bluegill	Lemly 1993 from Chapman 2007	Equivalent to WB 4 µg/g dw	Synthesis		Egg: 10	N
Various species	EPA 2004 from Chapman 2007	21 studies of 8 fish species (warm and cold water); used EPA (2004) to convert 7.9 µg/g dw WB to egg	Synthesis		Egg: 17	N
Various species	Cumbie and Van Horn 1978; Lemly 1985, 1997, 1998a, 2002	16 species extirpated; 10–70% rates of teratogenesis	Field	Species extirpation; teratogenesis	WB: 40–125 Muscle: 25–200 Egg: 20–170	N

Equations used to translate between whole-body and egg/ovary:

FHM [Se] dw WB = 0.75826*(FHM [Se] dw ovary) - 0.78645 (GEI 2008)

BG log[Se] dw WB = 0.73*(BG log[Se] dw ovary) + 0.06 (GEI et al. 2008)

BG log[Se] dw WB = 0.90*(BG log[Se] dw egg) – 0.31 (GEI et al. 2008)

TROUT log[Se] dw WB = 0.75*(TROUT log[Se] dw egg) + 0.04 (GEI et al. 2008)

ALL SPECIES log[Se] dw WB = 0.7851*(ALL SPECIES log[Se] dw egg) + 0.01 (modified herein from GEI et al. 2008; see Appendix A)

BG [Se] dw WB = 0.46337*(BG [Se] dw ovary) + 0.01728 (EPA 2004)

Table 3: Selenium toxicity data available for Virginia fish species used to calculate GMCVs. CV = Chronic Value, GMCV = Genus Mean Chronic Value, WB = whole-body.

Species	Endpoint	Reference	Whole-body			Egg/Ovary		
			CV µg/g	GMCV µg/g	WB Rank	CV µg/g	GMCV µg/g	Egg/Ovary Rank
Lepomis macrochirus Bluegill	Juvenile mortality LOEC	Lemly 1993	7.91	8.9	1	17.01	22	4/5/6
	Larval edema EC_{10}	Hermanutz et al. 1992, 1996	7.7			30		
	Larval survival EC_{10}	Coyle et al. 1993	8			23		
	Larval edema EC_{10}	Doroshov et al. 1992	8.12			18.3		
	Juvenile mortality 4°C EC_{10}	McIntyre et al. 2008	9.56			18.3		
	Juvenile mortality 9°C EC_{10}	McIntyre et al. 2008	13.29			28.6		
Salvelinus fontinalis Brook trout	Craniofacial deformities NOEC	Holm 2000; Holm et al. 2003; Holm et al. 2005	>10.34	10.3	2	>20	20	1
Esox lucius Northern pike	Larval deformities EC_{10}	Muscatello et al. 2006	10.92	10.92	3	20.4	20.4	2
Micropterus salmoides Largemouth bass	Larval mortality EC_{10}	CP&L 1997	10.96	11	4	22	22	4/5/6
Salmo trutta Brown trout	Larval deformities EC_{10}	NewFields 2009	11.14	11.1	5	22	22	4/5/6
Acipenser transmontanus White sturgeon	Larval growth EC_{10}	Tashjian et al. 2006	15	11.4	6	30.6	21.6	3
	Larval deformities EC_{10}	Linville 2006	8.71			15.3		
Oncorhynchus mykiss Rainbow trout	Skeletal deformities EC_{10}	Holm 2000; Holm et al. 2003; Holm et al. 2005	11.52	11.5	7	23	23	8
Gambusia holbrooki Eastern mosquitofish	Brood size/offspring viability NOEC	Staub et al. 2004	>11.85	11.85	8	>22.6	22.6	7
Catostomus commersonii White sucker	Larval deformities EC_{13}	de Rosemond et al. 2005	13.05	13.05	9	25.6	25.6	9
Pimephales promelas Fathead minnow	Larval deformities EC_{10}	GEI 2008	33	31	10	45	42	10
	Larval edema/lordosis LOEC	Schultz and Hermanutz 1990	<28.99			<39.27		

3.2.1.1 Bluegill and Other Centrarchid Data

The application of the Lemly (1993) values for bluegill in the 2004 draft document is as follows:

> "Given the uncertainty of juvenile fish concentration Se over the winter, a final chronic value (FCV) of 7.91 µg Se/g dw is recommended. However, if the concentration of Se in whole body fish tissues approaches 5.85 µg Se/g dw during summer or fall months, it is recommended fish be sampled during winter to determine if they exceed the FCV of 7.91 µg Se/g dw."

Lemly (1993) presents data on the combined effects of winter stress (water temperature of 4°C) and tissue Se concentrations on fish mortality. When the 2004 draft document was written, this was the only study that specifically evaluated potential seasonal effects on Se toxicity. In 2008, EPA conducted a similar study (McIntyre et al. 2008) using water temperatures of 4°C and 9°C, and reported EC_{10}s of 9.56 and 13.3 µg/g wb dw, respectively. In addition to the new EPA laboratory studies, there are a number of field mesocosm experiments in which Se exposure started in late summer and continued through winter and into spawning in the spring (Hermanutz et al. 1996, Hamilton et al. 2002). These data, thus, include a "winter stress" component in natural systems, more comparable to real-life conditions than modeling winter stress in the laboratory. Both studies exposed test organisms to more than one water and dietary Se concentration, yet neither of these studies report excessive additional mortality of Se exposed test organisms during winter months resulting from Se exposures. As such, they do not support direct application of the Lemly (1993) "winter stress" study to Virginia waters, at least in terms of use of a single value from that study.

Given winter stress may not be directly applicable to all species or sites in Virginia, we believe it is more appropriate to simply include the Lemly (1993) values and other relevant studies into an overall species mean chronic value (SMCV) calculation for bluegills, following EPA criteria development guidelines (Stephan et al. 1985). Many values from other sources were derived from offspring mortality endpoints, which are frequently considered more sensitive endpoints than juvenile or adult mortality for many species (Gillespie and Baumann 1986, Schultz and Hermanutz 1990, Coyle et al. 1993, Holm et al. 2003).

A total of 12 chronic values are available for bluegill — six for whole-body and six for egg/ovary (Tables 2 and 3). EPA did not include chronic values from studies in which eggs and larvae were obtained from bluegill adults previously exposed to elevated Se for multiple generations (Bryson et al. 1984 and 1985a,b, Gillespie and Baumann 1986). We also excluded these values from our chronic value calculation for the centrarchid family.

In addition to excluding data points from potentially acclimated test organisms, the EPA did not include chronic values from Lemly (1993) of > 6.0 µg/g, Cleveland et al. (1993), and Hermanutz et al. (1996) in the *Lepomis* SMCV calculation, without giving a detailed explanation of why they were excluded. Exclusion of the Lemly data point is understandable since the other reported tissue concentration from this study at which a significant effect was observed is also in the database and used in the SMCV calculations. In addition, it is reasonable to exclude data from Cleveland et al. (1993) because this study utilized only aqueous exposure, which is not relevant for a bioaccumulative parameter like Se. The reason for excluding data from Hermanutz et al. (1996) is not as apparent, as their values are well within the range reported for this species. This is especially problematic since one of the toxicological endpoints measured in Hermanutz et al. (1996) was larval edema, which was often selectively used by the EPA over remaining data for other fish species for SMCV calculations (e.g., fathead minnows). Therefore, we support the inclusion of this data point in a revised SMCV calculation for bluegills.

In addition to the Lemly (1993) and Hermanutz et al. (1996) data, only three other studies were deemed usable: Doroshov et al. (1992), Coyle et al. (1993), and McIntyre et al. (2008). Results from recent studies by WVDEP (2010) were deemed unusable due to the lack of matched adult and egg/ovary tissue concentrations and measured larval response.

The usable bluegill data from Lemly (1993) and McIntyre et al. (2008) were originally published as whole-body Se concentrations. These values were translated to whole-body concentrations using the bluegill ovary to whole-body translation equation in GEI et al. (2008), which updated the Equation II used in EPA (2004).

Data are available for another centrarchid species, the largemouth bass (CP&L 1997). This data point was originally published as an ovary concentration and was translated to a whole-body concentration using the bluegill ovary to whole-body translation equation in GEI et al. (2008), as no other equation is available for this member of the centrarchid family.

3.2.1.2 Trout and Other Salmonid Data

Data for cutthroat trout (Hardy 2005), Yellowstone cutthroat (Hardy et al. 2010, Formation Environmental 2011), westslope cutthroat trout (Kennedy et al. 2000, Nautilus Environmental 2011, Rudolph et al. 2008), and dolly varden (Golder 2009) were not used in our analysis because these species do not occur in Virginia. However, other Salmonidae data for species that do occur in Virginia are available and were evaluated.

Chronic toxicity data are available for rainbow trout (Holm 2000, Holm et al. 2003, Holm et al. 2005, Hodson et al. 1980, Hunn et al. 1987, Vidal et al. 2005), brook trout (Holm 2002, Holm et al. 2003), and brown trout (NewFields 2009). While both data points for brook trout and brown trout were deemed usable (Table 2), only one of the rainbow trout data points (the EC_{10} value derived from data presented in Holm 2000, Holm et al. 2003, Holm et al. 2005) is useable for criteria calculation. The two rainbow trout studies deemed unusable (Hodson et

al. 1980 and Hunn et al. 1987) were both aqueous only exposure studies, which are not environmentally relevant for a bioaccumulative element such as Se (DeForest and Adams 2011).

These usable rainbow trout, brook trout, brown trout data were originally published as egg Se concentrations. These values were translated to whole-body concentrations using the trout egg to whole-body translation equation in GEI et al. (2008).

3.2.1.3 Minnow Data

Several data points are available for the fathead minnow; however, most of these data were deemed unusable for the reasons discussed below.

A study on fathead minnows by Bertram and Brooks (1986) was not used to derive the chronic criterion. Bertram and Brooks (1986) reported a whole-body no observable effect concentration (NOEC) for growth of >2.2 µg/g. However, the authors were simply assessing Se uptake and depuration (i.e., Se kinetics), not Se toxicity. Fathead minnow growth was monitored for the purpose of determining if the model assumption that organisms did not grow was met (i.e., physiological 'steady state'). This test was not deemed appropriate for use in the criteria derivation for the following reasons: 1) The tested concentrations of Se were very low compared to tests designed to assess Se toxicity, resulting in an unbounded NOEC value much lower than any other value in the usable database; and 2) The purpose of the test was to evaluate Se kinetics, *not* to measure Se toxicity through effects on growth.

Four studies that investigated chronic Se toxicity in cyprinids were evaluated in the draft Se criteria document (EPA 2004). All of these studies investigated toxic effects in adult and larval fathead minnow. Chronic fathead minnow effect estimates were derived from three laboratory-based studies (Bennett et al. 1986, Dobbs et al. 1996, Ogle and Knight 1989) and one field and mesocosm study (Schultz and Hermanutz 1990). The three laboratory studies involved exposing adult fathead minnow to waterborne Se and Se spiked food. Resulting larval fish were analyzed and growth effects were modeled with respect to adult whole-body Se concentrations. Reduced larval growth was the chosen effect in the respective laboratory study, and chronic values were <43, <76, and >7.5 µg/g wb dw, respectively, for the three lab studies. Due to the extreme range in chronic values, dietary exposure uncertainties, and endpoint determination issues, the three laboratory-based studies were deemed unacceptable by EPA for criteria derivation.

Schultz and Hermanutz (1990) conducted a mesocosm study to examine effects of Se in fathead minnow larvae. This study was unique in that the exposure route was waterborne and dietary. Adult fathead minnows were originally exposed to selenite, which was added to artificial streams. Embryo samples were collected from spawning platforms and reared in the laboratory in natural water containing 10 µg Se/L. Edema (abnormal fluid accumulation) and lordosis (curvature of the spine) were observed in approximately 25 percent of the larvae. The mean Se residues in the ovaries of females from the treated stream were

39.27 µg/g. Maternal whole-body Se samples were not analyzed. To estimate whole-body Se tissue concentrations, we applied an ovary-to-whole body tissue model derived using fathead minnow data (GEI 2008). The resulting whole-body chronic value for this study was estimated to be <28.99 µg/g dw. It should be noted that EPA (2004) reported this value as <18.21, based on translation from whole-body using their Equation II. We believe our value based on a conversion using species-specific regressions is the better number. Although an undefined value derived from an ovary-to-whole body regression, this was the only fathead minnow chronic study that was deemed acceptable by EPA for criteria derivation.

Because cyprinids are often the dominant taxa of many warm water streams, and were only represented by the one undefined value in 2004 draft chronic database, we conducted a maternal Se transfer study for this species (GEI 2008). This study was modeled from the mesocosm and laboratory study conducted by Schultz and Hermanutz (1990) and a similar field and laboratory study using trout conducted Holm et al. (2005). The resulting final chronic value (40.0 µg/g wb dw) was based on a maternal transfer-based larval graduated severity index for deformities (GSI) that incorporated skeletal, edema, finfold, and craniofacial abnormality assessment results. This chronic value is within the range of fathead minnow values from studies reviewed by the EPA in draft criteria development (EPA 2004). However, to be more conservative, we used the EC_{10} values, based on larval skeletal and edema abnormality, to calculate the chronic criterion. The resulting EC_{10} values for whole-body and egg/ovary are 33 and 45 µg/g dw, respectively (GEI 2008). These values were used with the Schultz and Hermanutz (1990) values to derive GMCVs for fathead minnows (Table 3).

3.2.1.4 Catostomid Data

Data for the razorback sucker (Hamilton et al. 2005a,b) were not used because this species does not occur in Virginia. However, Catostomidae data for species that do occur in Virginia are available, and were evaluated.

Useable data for the white sucker are available from a study by de Rosemond et al. (2005). This usable data point was originally published as egg Se concentration and was translated to whole-body concentration using the "all species" egg to whole-body translation equation modified from the equation in GEI et al. (2008).

3.2.1.5 Other Species Data

Useable data points are available for three other species which occur or represent species that could occur in Virginia, which include: northern pike (Muscatello et al. 2006), eastern mosquitofish (Staub et al. 2004), and white sturgeon (Linville 2006, Tashjian et al. 2006).

The northern pike and white sturgeon (Linville 2006) data were originally published as egg Se concentrations. These values were translated to whole-body concentrations using the "all species" egg to whole-body translation equation modified from the equation in GEI et al.

(2008). Similarly, the eastern mosquitofish and white sturgeon (Tashjian et al. 2006) data were originally published as whole-body Se concentrations, so these values were translated to egg/ovary concentrations using the same equation.

While there are several species in the family Ictaluridae (catfish) that occur in Virginia, the only known chronic data for this family are from an unusable study by Doroshov et al. (1992). This study evaluated effects of directly injected seleno-L-methionine on channel catfish; direct injection is not an environmentally relevant method of exposure and EPA has rejected use of all studies based on this method of exposure in prior drafts of their Se criteria document (EPA 2004). Therefore, this study was also excluded from our analysis. Similarly, data derived through injection studies by Linville (2006) were also excluded.

3.2.1.6 Data Summary

Genus mean chronic values were derived for 10 species (Table 3). Based on this analysis of appropriate and relevant data, it appears that the bluegill remains the most Se-sensitive species in Virginia, when whole-body data are considered (Table 3), while brook trout are the most sensitive based on egg/ovary data

3.2.1.7 Chronic Criteria calculations

The recalculated final chronic value (FCV) was determined for both whole-body and egg/ovary using the GMCVs for the four most sensitive genera in the revised chronic database (Tables 4 and 5). Calculations followed the 1985 Guidelines for criteria derivation (Stephan et al. 1985) and are presented in Tables 4 and 5. Because these calculations represent an explicit use of the 1985 Guidelines, the resulting criteria are vastly improved over EPA's draft criterion (EPA 2004), which was based on a single value. The recalculated FCV for whole-body is 8.6 µg/g, whereas the FCV for egg/ovary is 19.3 µg/g – both as dry weight.

Table 4: Calculation of the final chronic values for whole-body Se using the updated chronic database (N = 10 genera, R = sensitivity rank in database, P = rank / N+1).

Rank	Genus	GMCV	ln GMCV	(ln GMCV)^2	P = R/(N+1)	√P
1	*Lepomis*	8.92	2.1883	4.7886	0.0909	0.30151
2	*Salvelinus*	10.34	2.3360	5.4570	0.1818	0.42640
3	*Esox*	10.9	2.3906	5.7149	0.2727	0.52223
4	*Micropterus*	11.0	2.3943	5.7324	0.3636	0.60302
		Sum	9.3092	21.6930	0.9091	1.85317

Calculations:

Chronic Whole-body Criterion

$S^2 = \frac{\Sigma (\ln GMCV)^2 - (\Sigma \ln GMCV)^2/4}{\Sigma P - (\Sigma \sqrt{P})^2/4} = \frac{21.6930 - (9.3092)^2/4}{0.9091 - (1.85317)^2/4} = 0.5519 \quad S = 0.7429$

$L = [\Sigma \ln GMCV - S(\Sigma \sqrt{P})]/4 = [9.3092 - 0.7429\ (1.85317)]/4 = 1.9831$

$A = S\ (\sqrt{0.05}) + L = (0.7429)(0.2236) + 1.9831 = 2.1492$

Final Chronic Value = $FCV = e^A = 8.5783$

Table 5: Calculation of the final chronic values for egg/ovary Se using the updated chronic database (N = 10 genera, R = sensitivity rank in database, P = rank / N+1).

Rank	Genus	GMCV	ln GMCV	(ln GMCV)^2	P = R/(N+1)	√P
1	*Salvelinus*	20	2.9957	8.9744	0.0909	0.30151
2	*Esox*	20.4	3.0155	9.0935	0.1818	0.42640
3	*Acipenser*	21.6	3.0745	9.4528	0.2727	0.52223
4	*Lepomis*	22	3.0910	9.5545	0.3636	0.60302
		Sum	12.1769	37.0752	0.9091	1.85317

Calculations:

Chronic Egg/Ovary Criterion

$S^2 = \frac{\Sigma (\ln GMCV)^2 - (\Sigma \ln GMCV)^2/4}{\Sigma P - (\Sigma \sqrt{P})^2/4} = \frac{37.0752 - (12.1769)^2/4}{0.9091 - (1.85317)^2/4} = 0.1244 \quad S = 0.3527$

$L = [\Sigma \ln GMCV - S(\Sigma \sqrt{P})]/4 = [12.1769 - 0.3527\ (1.85317)]/4 = 2.8808$

$A = S\ (\sqrt{0.05}) + L = (0.3527)(0.2236) + 2.8808 = 2.9597$

Final Chronic Value = $FCV = e^A = 19.2918$

4.0 Implementation Recommendations

4.1 Acute Se

We would recommend deleting the current acute Se criterion of 20 µg/L and replacing it with the EPA footnote equation (EPA 2012) for Se:

$$CMC = 1/[f1/CMC1)+(f2/CMC2)],$$

where f1 and f2 are the fraction of total Se that are comprised as selenite (Se^{+4}) and selenate (Se^{+6}), respectively. In addition, we would recommend use of the updated values for sulfate, where CMC1 = 258 µg/L for selenite and CMC2 = $e^{(0.5812[\ln(\text{sulfate})]+3.357)}$, consistent with EPA (2004) updates – not the values currently cited in EPA (2012), which are based on the outdated 1987 criteria document. If Se speciation is not conducted, the more conservative value of 258 µg/L would be applied (if sulfate is greater than 44 mg/L at a site – see Table 1 for example values at varying sulfate concentrations).

4.2 Chronic Se

Based on the current science, it is known that tissue Se concentrations better represent actual Se exposure and uptake by aquatic life. However, implementation of a tissue-based threshold is potentially difficult for regulators and the regulated community, as attainment assessments would require collection of fish tissue data on a regular basis in a wide variety of aquatic habitats – and potentially collection during the reproductive cycle of multiple resident fish species, given potential use of egg/ovary Se criteria.

Thus, we would recommend a tiered approach that would retain the 5 µg/L total Se value as the primary standard for initial assessment of attainment of the Se chronic standard, and employ a tissue-based standard as needed in a tiered approach. This is similar to the multi-step implementation approach we understand will be central to EPA's update, which we believe will include a default water column value, supported by a tissue-based criterion. Such an approach would require the discharger to demonstrate compliance/non-compliance with the default water column value first. If the water column value is met, no further assessment is needed. If the water column value is exceeded, fish tissue (whole-body or egg/ovary) would be collected and compared to the thresholds calculated above. Specifics for implementation, such as sample size and summary statistics, could be made consistent with Virginia's guidance. The suggested tiered approach is as follows:

Step 1. Determine if site is in attainment of the 5 µg/L water column-based standard.

- If water quality is below 5 µg/L, the analysis is complete and water-body is considered in attainment.
- If water quality is greater than 5 µg/L, proceed to Step 2.

Step 2. Determine if the site is in attainment of the tissue threshold (whole-body [8.6 µg/g] or egg/ovary [19.3 µg/g]).

- If tissue Se concentrations are less than the appropriate tissue-based standard, the analysis is complete and the water-body is considered in attainment.
- If the site tissue Se concentrations exceed the tissue-based standard, the site is considered in non-attainment, and evaluation of Se sources and effects is necessary.
- Results of this step may include an analysis of whether the Se source is natural or anthropogenic, and also if Se is negatively impacting aquatic life populations. These analyses could be accomplished through detailed sampling and analysis of fish populations, as well as determination of sources/fate of Se in the affected waterbody.

5.0 Summary

Virginia's current aquatic life standards for Se are based on recommendations from the EPA's 1987 Se criteria document (EPA 1987). These standards are not based on laboratory-derived toxicity data and do not represent the current state of the science. While EPA has been in the process of reviewing and updating the national Se criteria for over 15 years, with draft criteria documents released in 2002 and 2004, neither version was ever finalized and EPA is currently working on yet another major revision. The 2004 draft was based on whole-body fish tissue Se concentrations, and it is expected that the new criteria will also be fish tissue-based (whole-body and/or egg/ovary). It is expected that the new national criteria currently in development may also take a "tiered approach" that includes both water column and tissue Se thresholds.

Rather than wait for this update, states can and should develop their own updated criteria instead of relying on the outdated and inappropriate criteria from 1987. Thus, we recommend that Virginia adopt the following acute and chronic Se standards:

Acute

Acute = 1/[f1/CMC1)+(f2/CMC2)]

Where:

f1 and f2 are the fraction of total Se that are comprised as selenite (Se^{+4}) and selenate (Se^{+6}), respectively

CMC1 = 258 µg/L for selenite
CMC2 = $e^{(0.5812[\ln(\text{sulfate})] - 3.357)}$ for selenate

Chronic

Chronic Tiered Standards:

Initial screening: 5 µg/L water column
Follow-up screening: 19.3 µg/g (dw) egg/ovary tissue
8.6 µg/g (dw) whole-body tissue

6.0 References

Bennett, W.N., A.S. Brooks, and M.E. Boraas. 1986. Selenium uptake and transfer in an aquatic food chain and its effects on fathead minnow (*Pimephales promelas*) larvae. *Archives of Environmental Contamination and Toxicology* 15(5):513-517.

Bertram, P.E., and A.S. Brooks. 1986. Kinetics of accumulation of selenium from food and water by fathead minnows. *Water Research* 20:877-884.

Brix K.V., J.S. Volosin, W.J. Adams, R.J. Reash, R.G. Carlton, and D.O. McIntyre. 2001a. Effects of sulfate on the acute toxicity of selenate to freshwater organisms. *Environmental Toxicology and Chemistry* 20:1037-1045.

Brix, K.V., W.J. Adams, R.J. Reash, R.C. Carlton, and D.O. McIntyre. 2001b. Acute toxicity of selenate on two daphnids and three gammarid amphipods. *Environmental Toxicology and Chemistry* 16: 142-150.

Bryson, W.T., W.R.Garrett, M.A. Mallin, K.A. MacPherson, W.E. Partin, and S.E. Woock. 1984. Roxboro Steam Electric Plant 1982 Environmental Monitoring Studies, Volume II, Hyco Reservoir. Bioassay Studies. Environmental Technology Section. Carolina Power & Light Company.

Bryson, W.T., W.R.Garrett, M.A. Mallin, K.A. MacPherson, W.E. Partin, and S.E. Woock. 1985a. Roxboro Steam Electric Plant Hyco Reservoir 1983 Bioassay Report. Environmental Sevices Section. Carolina Power & Light Company. September 1985.

Bryson, W.T., K.A. MacPherson, M.A. Mallin, W.E. Partin, and S.E. Woock. 1985b. Roxboro Steam Electric Plant Hyco Reservoir 1984 Bioassay Report. Environmental Services Section. Carolina Power & Light Company.

Canton, S.P. 1999. Acute aquatic life criteria for selenium. *Environmental Toxicology and Chemistry* 18:1425-1432.

Carolina Power & Light (CP&L). 1997. Largemouth Bass Selenium Bioassay- Report. Carolina Power & Light Company, Environmental Services Section, NC. December 1997.

Chapman, P.M. 2007. Selenium thresholds for fish from cold freshwaters. *Human and Ecological Risk Assessment* 13:20-24.

Cleveland, L., E.E. Little, D.R. Buckler, and R.H. Wiedmeyer. 1993. Toxicity and bioaccumulation of waterborne and dietary selenium in juvenile bluegill (*Lepomis macrochirus*). *Aquatic Toxicology* (Amsterdam) 27(3-4):265-279.

Coyle, J.J., D.R. Buckler, C.G. Ingersoll, J.F. Fairchild, and T.W. May. 1993. Effect of dietary selenium on the reproductive success of bluegills *Lepomis macrochirus*. *Environmental Toxicology and Chemistry* 12(3):551-565.

Cumbie, P.M., and S.L. Van Horn. 1978. Selenium accumulation associated with fish mortality and reproductive failure. *Proceedings of the Annual Conference of the Southeastern Association of Fish and Wildlife Agencies* 32:612-624.

DeForest, D.K., K.V. Brix, and W.J. Adams. 1999. Critical review of proposed residue-based selenium toxicity thresholds for freshwater fish. *Human and Ecological Risk Assessment* 5:1187-1228.

DeForest D.K., and W.J. Adams. 2011. Selenium accumulation and toxicity in freshwater fishes. pp. 193-229. In: Beyer, W.N., and J.P. Meador, editors. *Environmental contaminants in biota: interpreting tissue concentrations.* 2nd edition. Boca Raton (FL, USA): Taylor and Francis.

DeForest D.K., G. Gilron, S.A. Armstrong, and E.L. Robertson. 2012. Species sensitivity distribution evaluation for selenium in fish eggs: Considerations for development of a Canadian tissue-based guideline. *Integrated Environmental Assessment and Management* 8:6-12.

de Rosemond, S.C., K. Liber, and A. Rosaasen. 2005. Relationship between embryo selenium concentration and early life stage development in white sucker (*Catostomus commersoni*) from a northern Canadian lake. *Bulletin of Environmental Contamination and Toxicology* 74:1134-1142.

Dobbs, M.G., D.S. Cherry, and J. Cairns, Jr. 1996. Toxicity and bioaccumulation of selenium to a three-trophic level food chain. *Environmental Toxicology and Chemistry* 15:340-347.

Doroshov, S., J.V. Eenennaam, C. Alexander, E. Hallen, H. Bailey, K. Kroll, and C. Restreppo. 1992. Development of water quality criteria for resident aquatic species of the San Joaquin River. Draft final report to the California State Water Resources Control Board for Contract No. 7-197-250-0. Department of Animal Science, University of California, Davis, CA.

Engberg, R.A., D.W. Westcot, M. Delamore, and D.D. Holz. 1998. Federal and State perspectives on regulation and remediation of irrigation-induced selenium problems. Pages 153-182 *in* W.T. Frankenberger Jr. and R.A. Engberg, eds. *Environmental Chemistry of Selenium.* Marcel Dekker Inc., New York.

Faust, S.D., and O.M. Aly. 1981. *Chemistry of Natural Waters.* Ann Arbor Science, Ann Arbor, MI. pp. 359-371.

Formation Environmental. 2011. Yellowstone cutthroat trout laboratory reproduction studies conducted in support of development of a site-specific selenium criterion. Draft. Prepared for J.R. Simplot Company. Pocatello (ID):Smoky Canyon Mine.

GEI Consultants, Inc. (GEI). 2008. Maternal transfer of selenium in fathead minnows, with modeling of ovary tissue-to-whole body concentrations. Technical Report prepared on behalf of Conoco-Phillips.

GEI Consultants, Inc., Golder Associates, Parametrix, and University of Saskatchewan Toxicology Centre. 2008. Selenium tissue thresholds: tissue selection criteria, threshold development endpoints, and field application of tissue thresholds. Report to: North American Metals Council-Selenium Working Group, Washington, DC. http://namc.org/docs/00043675.PDF.

Gillespie, R.B. and P.C. Baumann. 1986. Effects of high tissue concentrations of selenium on reproduction by bluegills (*Lepomis macrochirus*). *Transactions of the American Fisheries Society* 115(2):208-213.

Golder Associates. 2009. Development of a site-specific selenium toxicity threshold for Dolly Varden Char. Report Number 04-1421-101/2000. Report to Northgate Minerals Corporation, Smithers, British Columbia.

Hamilton, S.J. 2002. Rationale for a tissue-based selenium criterion for aquatic life. *Aquatic Toxicology* 57:85-100.

Hamilton, S.J. 2003. Review of residue-based selenium toxicity thresholds for freshwater fish. *Ecotoxicology and Environmental Safety* 56:201-210.

Hamilton, S.J., K.J. Buhl, N.L. Faerber, R.H. Wiedmeyer, and F.A. Bullard. 1990. Toxicity of organic selenium in the diet to Chinook salmon. *Environmental Toxicology and Chemistry* 9(3):347-358.

Hamilton, S.J., K.M. Holley, K.J. Buhl, F.A. Bullard, L.K. Weston, and S.F. McDonald. 2002. Impact of selenium and other trance elements on the endangered adult razorback sucker. *Environmental Toxicology* 17:297-323.

Hamilton, S.J., K.M. Holley, K.J. Buhl, F.A. Bullard, K.L. Weston, and S.F. McDonald. 2005a. Selenium impacts on razorback sucker, Colorado River CO: I. Adults. *Ecotoxicology and Environmental Safety* 61:7-31.

Hamilton, S.J., K.M. Holley, K.J. Buhl, and F.A. Bullard. 2005b. Selenium impacts on razorback sucker, Colorado River CO: II. Eggs. *Ecotoxicology and Environmental Safety* 61:32-43.

Hardy, R.W. 2005. Effects of dietary selenium on cutthroat trout (*Oncorhynchus clarkii*) growth and reproductive performance. Final report prepared for Montgomery Watson Harza (MWH), Bellevue, WA by University of Idaho, Aquaculture Research Institute, Hagerman, ID. December 14, 2005. 44 pp.

Hardy R.W., L. Oram, and G. Möller. 2010. Effects of dietary selenomethionine on cutthroat trout (*Oncorhynchus clarki bouvieri*) growth and reproductive performance over a life cycle. *Archives of Environmental Contamination and Toxicology* 58:237-245.

Hermanutz, R.O., K.N. Allen, T.H. Roush, and S.F. Hedtke. 1992. Effects of elevated Se concentrations on bluegills (*Lepomis macrochirus*) in outdoor experimental streams. *Environmental Toxicology and Chemistry* 11:217-224.

Hermanutz, R.O., K.N. Allen, N.E. Detenbeck, and C.E. Stephan. 1996. Exposure of bluegill (*Lepomis macrochirus*) to selenium in outdoor experimental streams. U.S. EPA Report. Mid-Continent Ecology Division. Duluth, MN.

Hodson, P.V., D.J. Spry, and B.R. Blunt. 1980. Effects on rainbow trout (*Salmo gairdneri*) of a chronic exposure to waterborne selenium. *Canadian Journal of Fisheries and Aquatic Science* 37:233-240.

Holm, J. 2002. Sublethal effects of selenium in rainbow trout (*Oncorhynchus mykiss*) and brook trout (*Salvelinus fontinalis*) [MA thesis]. Winnipeg (MB):Univ Manitoba.

Holm, J., V.P. Palace, K. Wautier, R.E. Evans, C.L. Baron, C. Podemski, P. Siwik, and G. Sterling. 2003. An assessment of the development and survival of rainbow trout (*Oncorhynchus mykiss*) and brook trout (*Salvelinus fontinalis*) exposed to elevated selenium in an area of active coal mining. Proceedings of the 26th Annual Larval Fish Conference 2003, Bergen, Norway. ISBN 82-7461-059-B.

Holm J., V. Place, P. Siwik, G. Sterling, R. Evans, C. Baron, J. Werner, and K. Wautier. 2005. Developmental effects of bioaccumulated selenium in eggs and larvae of two salmonid species. *Environmental Toxicology and Chemistry* 24(9):2373-2381.

Hunn, J.B., S.J. Hamilton, and D.R. Buckler. 1987. Toxicity of sodium selenite to rainbow trout fry. *Water Research* 21:233-238.

Kennedy, C.J., L.E. McDonald, R. Loveridge, and M.M. Strosher. 2000. The effects of bioaccumulated selenium on mortalities and deformities in the eggs, larvae and fry of a wild population of cutthroat trout. *Archives of Environmental Contamination and Toxicology* 39:46-52.

Lemly, A.D. 1985. Toxicology of selenium in freshwater reservoir: implications for environmental hazard evaluation and safety. *Ecotoxicology and Environmental Safety* 10:314-338.

Lemly, A.D. 1993. Metabolic stress during winter increases the toxicity of selenium to fish. *Aquatic Toxicology* (Amsterdam) 27(1-2):133-158.

Lemly, A.D. 1996. Selenium in aquatic organisms. In: Beyer, W.N., G.H. Heinz, and A.W. Redmon-Norwood (eds), Environmental Contaminants in Wildlife. Lewis Publishers, New York, NY, USA.

Lemly, A.D. 1997. Ecosystem recovery following selenium contamination in a freshwater reservoir. *Ecotoxicology and Environmental Safety* 36:275-281.

Lemly, A.D. 1998. A position paper on selenium in ecotoxicology: A procedure for deriving site-specific water quality criteria. *Ecotoxicology and Environmental Safety* 39:1-9.

Lemly, A.D. 2002. *Selenium Assessment in Aquatic Ecosystems: A Guide for Hazard Evaluation and Water Quality Criteria.* Springer-Verlag, NY.

Linville, R.G. 2006. Effects of excess selenium on the health and reproduction of white sturgeon (*Acipenser transmontanus*): Implications for San Francisco Bay-Delta [3250824]. United States -- California: University of California, Davis. 232 p.

Luoma, S.N., C. Johns, N.S. Fisher, N.A. Steinberg, R.S. Oremland, and J.R. Reinfelder. 1992. Determination of selenium bioavailability to a benthic bivalve from particulate and solute pathways. *Environmental Science and Technology* 26:485-491.

McIntyre, D.O., M.A. Pacheco, M.W. Garton, D. Wallschläger, and C.G. Delos. 2008. Effect of selenium on juvenile bluegill sunfish at reduced temperature. Health and Ecological Criteria Division, Office of Water, USEPA, Washington, DC. EPA-822-R-08-020.

Muscatello, J.R., P.M. Bennett, K.T. Himbeault, A.M. Belknap, and D.M. Janz. 2006. Larval deformities associated with selenium accumulation in northern pike (*Esox lucius*) exposed to metal mining effluent. *Environmental Science and Technology* 40:6506-6512.

Nautilus Environmental. 2011. Evaluation of the effects of selenium on early life stage development of westslope cutthroat trout from the Elk Valley, BC. Sparwood (BC): Elk Valley Selenium Task Force. Draft revised report.

NewFields. 2009. Brown trout laboratory reproduction studies conducted in support of development of a site-specific selenium criterion. February 5, 2009 Draft Report to J.R. Simplot Company. NewFields, Boulder, CO.

Ogle, R.S., and A.W. Knight. 1989. Effects of elevated foodborne selenium on growth and reproduction of the fathead minnow *Pimephales promelas*. *Archives of Environmental Contamination and Toxicology* 18(6):795-803.

Ohlendorf, H. 2008. Technical Justification for Proposed Fish and Bird Egg Standards. Technical Memo prepared by CH2M Hill for NSMP, Orange County, CA.

Payne, R.G. 2013. Update to Kentucky Water Quality Standards for Protection of Aquatic Life: Acute Selenium Criterion and Tissue-Based Selenium Chronic Criteria. Kentucky Cabinet for Energy and Environment, Department of Environmental Protection, Division of Water, Frankfort, KY.

Ralston, N.V.C., Unrine, J. and D. Wallschlager. 2008. Biogeochemisty and Analysis of Selenium and its Species. Report Prepared for the North American Metals Council – Selenium Working Group, Washington, DC. http://namc.org/docs/00043673.PDF.

Rudolph, B.-L., I. Andreller, and C.J. Kennedy. 2008. Reproductive success, early life stage development, and survival of westslope cutthroat trout (*Oncorhynchus clarkii lewisi*) exposed to elevated selenium in an area of active coal mining. *Environmental Science and Technology* 42:3109-3114.

Saiki, M.K., B.A. Martin, and T.M. May. 2004. Reproductive status of western mosquitofish inhabiting selenium-contaminated waters in the grassland water district, Merced County, California. *Archives of Environmental Contamination and Toxicology* 47:363-369.

Schultz, R., and R. Hermanutz. 1990. Transfer of toxic concentrations of selenium form parent to progeny in the fathead minnow. *Bulletin of Environmental Contamination and Toxicology* 45:568-573.

Staub, B.P., W.A. Hopkins, J. Novak, and J.D. Congdon. 2004. Respiratory and reproductive characteristics of eastern mosquitofish (*Gambusia holbrooki*) inhabiting a coal ash settling basin. *Archives of Environmental Contamination and Toxicology* 46:96-101.

Stephan, C.E., D.I. Mount, D.J. Hansen, J.H. Gentile, G.A. Chapman, and W.A. Brungs. 1985. Guidelines for deriving numerical national water quality criteria for the protection of aquatic organisms and their uses. PB85-227049. National Technical Information Service, Springfield, VA.

Tashjian, D.H., S.J. Teh, A. Sogomoyan, and S.S.O. Hung. 2006. Bioaccumulation and chronic toxicity of dietary L-selenomethionine in juvenile white sturgeon *(Acipenser transmontanus)*. *Aquatic Toxicology* 79:401-409.

U.S. Department of the Interior (USDI). 1998. Guidelines for interpretation of the biological effects of selected constituents in biota, water, and sediment. National Irrigation Water Quality Program Information Report No. 3. USDI, Denver, CO. November.

United States Environmental Protection Agency (EPA). 1976. Quality Criteria for Water. PB-263943 or EPA-440/9-76-023. National Technical Information Service, Springfield, VA.

United States Environmental Protection Agency (EPA). 1980. Ambient Water Quality Criteria for Selenium. EPA-440/5-80-070. National Technical Information Service, Springfield, VA.

United States Environmental Protection Agency (EPA). 1987. Ambient Water Quality Criteria for Selenium. EPA-440/5-87-006. National Technical Information Service.

United States Environmental Protection Agency (EPA). 1995. Ambient Water Quality Criteria for Selenium.

U.S. Environmental Protection Agency (EPA). 1999. Update of Ambient Water Quality Criteria for Ammonia. EPA-822-R-99-014. Office of Water, Washington, DC.

United States Environmental Protection Agency (EPA). 2002. Draft Aquatic Life Water Quality Criteria for Selenium. February 2002. Office of Water, Washington, DC.

U.S. Environmental Protection Agency (EPA). 2004. Draft Aquatic Life Water Quality Criteria for Selenium - 2004. EPA-822-D-04-001. Office of Water, Washington, DC.

U.S. Environmental Protection Agency (EPA). 2009. Draft 2009 Update Aquatic Life Ambient Water Quality Criteria for Ammonia – Freshwater. EPA-822-D-09-001. Office of Water, Washington, DC.

U.S. Environmental Protection Agency (EPA). 2012. National Recommended Water Quality Criteria. Office of Water. http://water.epa.gov/scitech/swguidance/standards/criteria/current/index.cfm#L.

Vidal, D., S.M. Bay, and D. Schlenk. 2005. Effects of dietary selenomethionine on larval rainbow trout (*Oncorhynchus mykiss*). *Archives of Environmental Contamination and Toxicology* 49:71-75.

Virginia Department of Environmental Quality (VDEQ). 2011. 9VAC25-260-140. Criteria for surface water.. Effective January 6, 2011. Virginia Department of Environmental Quality, Richmond, VA.

Virginia Department of Game and Inland Fisheries (VDGIF). 2013. Virginia Fishes. Virginia Department of Game and Inland Fisheries, Richmond, VA. http://www.dgif.virginia.gov/wildlife/fish/.

West Virginia Department of Environmental Protection (WVDEP). 2010. Selenium-induced developmental effects among fishes in select West Virginia waters. West Virginia Department of Environmental Protection, Charleston, WV.

Appendix A

Data used to derive an updated "All Species" egg/ovary to whole-body translation equation

Table A-1: Data used to derive the updated "All Species" (data for bluegill, fathead minnow, and cutthroat trout) translation equation. Bluegill and cutthroat trout data are from Appendix 1 of GEI et al. (2008) and fathead minnow data are from GEI (2008).

Study	Species	[Ovary Se]	[Whole-body Se]	Log[Ovary Se]	Log[Whole-body Se]
Coyle et al. 1993	Bluegill sunfish	2.1	0.9	0.3222193	-0.045757
		2.1	0.9	0.3222193	-0.045757
		8.3	2.9	0.9190781	0.462398
		12.5	4.9	1.09691	0.6901961
		25	7.2	1.39794	0.8573325
		41	16	1.6127839	1.20412
Hermanutz et al. 1996	Bluegill sunfish	0.35	1.95	-0.455932	0.2900346
		20.05	22.85	1.3021144	1.3588862
		5.25	2.45	0.7201593	0.3891661
		3.85	1.95	0.5854607	0.2900346
		10.1	3.5	1.0043214	0.544068
		12.35	6.15	1.091667	0.7888751
		34.8	15.45	1.5415792	1.1889285
		50.5	26.45	1.7032914	1.4224257
		29.35	11.85	1.4676081	1.0737184
		66	30.6	1.8195439	1.4857214
		5.3	2.3	0.7242759	0.3617278
		8.4	6.3	0.9242793	0.7993405
		9.5	5.3	0.9777236	0.7242759
		31.15	12	1.4934581	1.0791812
		19.55	13	1.2911468	1.1139434
		17.85	8.35	1.2516382	0.9216865
		19.1	17.35	1.2810334	1.2392995
Hermanutz et al. 1992	Bluegill sunfish	1	2.0	0	0.30103
		22.5	23.0	1.3521825	1.3617278
Hardy 2005*	Cutthroat trout	0.99	0.72	-0.004365	-0.142668
		3.8	2.57	0.5797836	0.4099331
		5.45	2.78	0.7363965	0.4440448
		18.0	6.4	1.2552725	0.80618
		1.64	1.2	0.2148438	0.0791812
		7.82	4.64	0.8932068	0.666518
		6.61	5.87	0.8202015	0.7686381
		5.05	9.1	0.7032914	0.9590414
		5.18	11.37	0.7143298	1.0557605
		16.04	5.61	1.2052044	0.7489629
GEI 2008	Fathead Minnow	3.17	1.63	0.5010593	0.2121876
		22.52	11.96	1.3525684	1.0777312
		44.12	42.17	1.6446355	1.6250036
		50.33	25.15	1.7018269	1.400538
		60.26	52.22	1.7800291	1.7178369

* Data from this study were reported as ovary or egg, so were combined with the ovary data for equation derivation.

Figure A-1: Modified "All-Species" regression using log-transformed egg/ovary and whole-body tissue selenium concentrations measured in bluegill, fathead minnow, and cutthroat trout.